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Final Report
NASA Grant NAG 5-955

University of Maryland
Mechanical Engineering Department
College Park, MD 20742

(NASA-CR-187394) [STUDY OF DESIGN KNOWLEDGE CAPTURE (DKC) SCHEMES IMPLEMENTED IN MAGNETIC BEARING APPLICATIONS] Final Report (Maryland Univ.) 33 p CSCL 14B

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ABSTRACT

A design knowledge capture (DKC) scheme was implemented using frame-based techniques. The objective of such a system is to capture not only the knowledge which describes a design, but also that which explains how the design decisions were reached. These knowledge types were labelled definitive and explanatory, respectively. Examination of the design process helped determine what knowledge to retain and at what stage that knowledge is used. A discussion of frames resulted in the recognition of their value to knowledge representation and organization. The FORMS frame system was used as a basis for further development, and for examples using magnetic bearing design. The specific contributions made by this research include:

- Determination that frame-based systems provide a useful methodology for management and application of design knowledge.
- Definition of specific user interface requirements; this consists of a window-based browser.
- Specification of syntax for DKC commands; and
- Demonstration of the feasibility of DKC by application to existing designs.

It was determined that design knowledge capture could become an extremely valuable engineering tool for complicated, long-life systems, but that further work was needed, particularly the development of a graphic, window-based interface.

DKC With A Magnetic Bearing

Magnetic bearings are becoming increasingly valuable as the identification and development of appropriate applications continue. *The Advanced Design and Manufacturing Laboratory* at the University of Maryland, College Park is performing extensive research into magnetic bearings as applied to inertial energy storage, machine spindle control, and vibration isolation [1, 2]. In all cases, suspending a load magnetically eliminates friction; the bearing type determines if operating power is required. There are three main types of magnetic bearings:

- Permanent Magnet (PM)
- Electro-Magnet (EM)
- Combination Electro and Permanent Magnet (EM/PM)

Magnetic bearings, along with its subclasses and the three particular systems under development at UMCP will be the example for DKC.

Energy Storage

The magnetic bearing at UMCP used for flywheel energy storage is a so-called pancake bearing. The pancake bearing is a radially-active, axially-passive magnetic bearing. That is, the permanent (passive) magnets support all axial loads, and the electro-magnets (active) support all radially loads. Proper control of electro-magnet currents provides proper radially positioning. The main configuration consists of a stack of four (4) ferromagnetic plates: two (2) inner (bias flux or magnet) plates, and two (2) outer (control) plates. Sandwiched between the inner plates are four (4) symmetrically placed permanent magnets, and sandwiched between each outer plate and the corresponding inner plate are four (4) electro-magnets. The electro-magnets are wire coils surrounding ferromagnetic control-pins which act as structural elements. To hold the assembly together, a bolt is placed as a centerpost, and fastened with a nut. The only

other item is epoxy, which is used to fill in slots cut into the magnet plates. (See Figure 1)

The components of the bearing are listed below.

- Magnet Plate Assembly (1)
  - Magnet Plates (processed) (2)
    - Magnet Plates (2)
    - Epoxy (as required)
  - Permanent Magnets (4)
- Control Plates (2)
- Pins (8)
- Control Coils (8)
- Bolt (1)
- Nut (1)

Machine Spindle Control

The UMCP spindle control bearing is of the EM type. It has electromagnet coils above and below the spindle for axial support, and electromagnet coils around the spindle at top and bottom for radial support. Sensor rings provide the data needed to drive the electromagnets. The components are listed below.

- Spindle (1)
- Thrust Bearing Upper Assembly (1)
  - Thrust Bearing Upper Plate (1)
  - Thrust Bearing Coil (1)
- Thrust Bearing Lower Assembly (1)
  - Thrust Bearing Lower Plate (1)
  - Thrust Bearing Coil (1)
- Axial Sensor Ring (1)

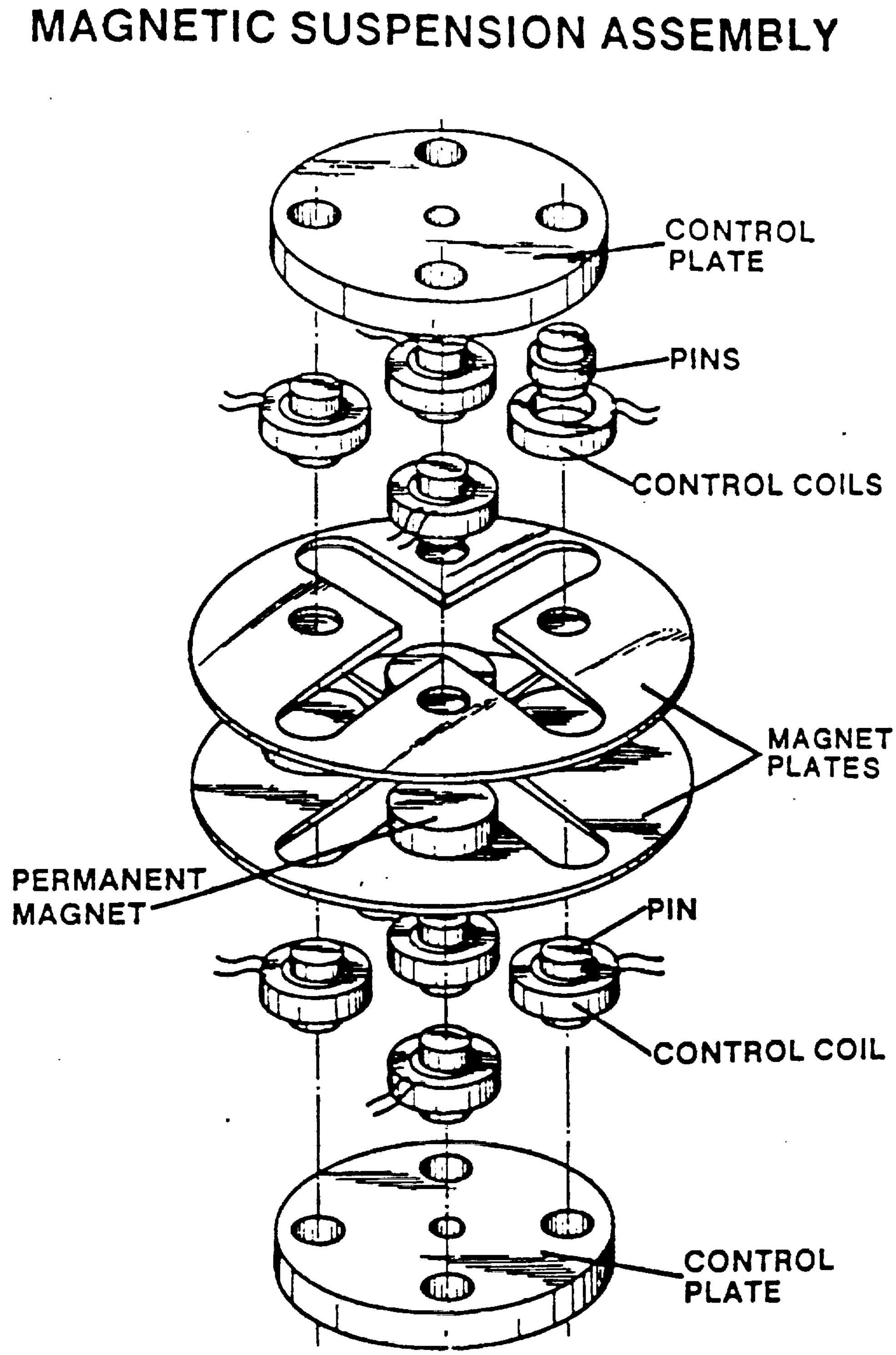

Figure 1. Magnetic Bearing Assembly Drawing.

- Radial Sensor Ring (2)
- Radial Bearing Top Assembly (1)
- Radial Bearing lower Assembly (1)
- Spindle Housing (1)
- Riser Block (1)

Vibration Isolation

The UMCP vibration isolation bearing supports a large, cantilevered, rotating load. (See Figure 2)

It too is an EM/PM, radially-active, axially-passive type. The main bearing configuration consists of 16 Rare Earth Cobalt (RECO) permanent magnets fit into a central ring which is sandwiched between two flux rings. An aluminum housing sandwiches eight electromagnet coils (four at each end) and all other pieces.

The components of this bearing are listed below.

- Central Ring (1)
- RECO Permanent Magnet (16)
- Flux Ring (2)
- Position Transducer Sensor (2)
- Pole Piece (8)
- Electromagnet Coil (8)
- Rotor Spindle Sleeve (1)
- Touchdown Ball Bearing (2)
- Draw Rod (8)
- Aluminum Housing (2)
- Wave Washer (8)
- Socket Head Cap Screw (8)

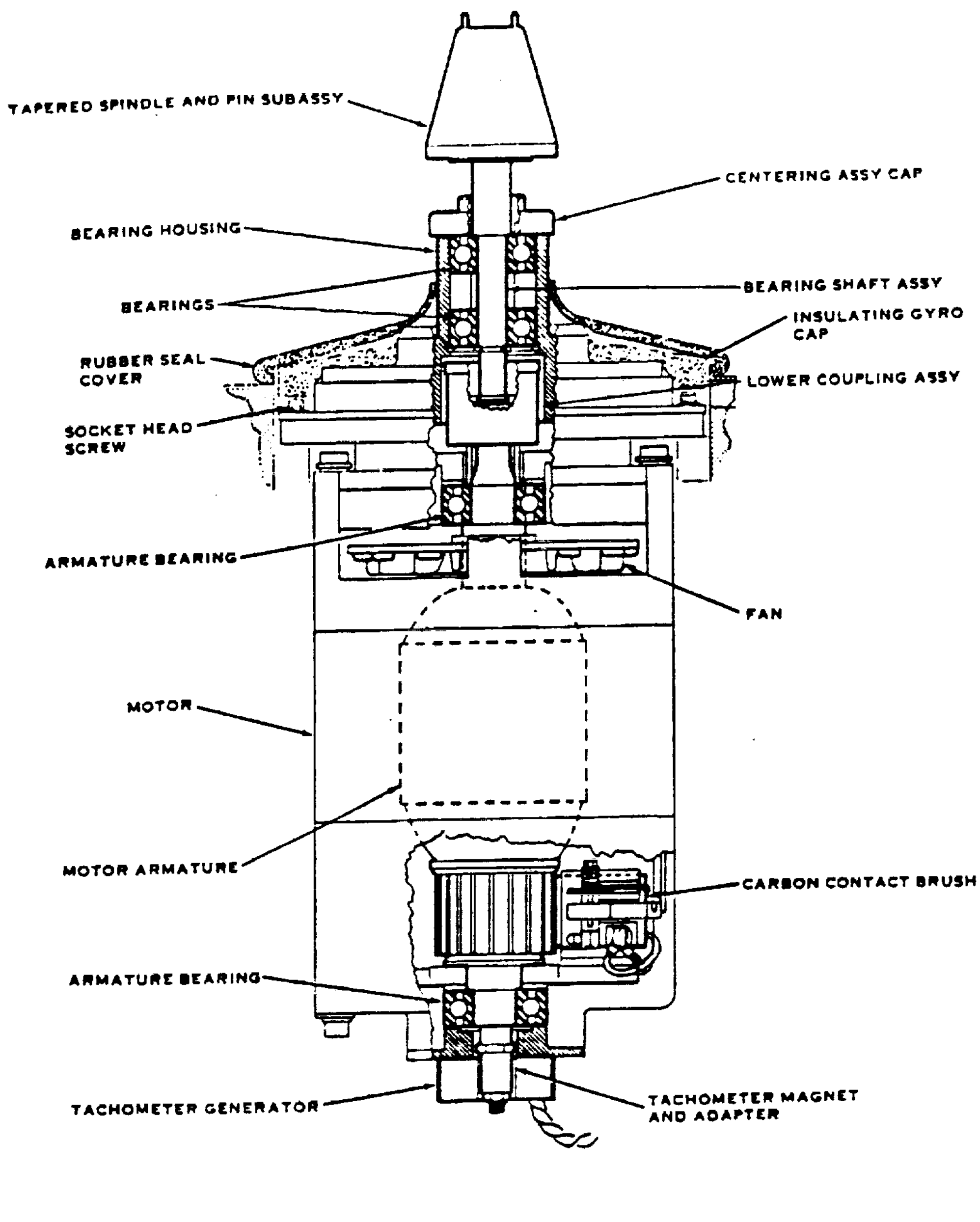

Figure 2. Vibration Isolation Magnetic Bearing Device.

The Magnetic Bearing Hierarchy

As described, the energy storage and vibration isolation bearings are instances of the design class of EM/PM magnetic bearings, while the spindle control bearing is an instance of the design class of EM magnetic bearings. EM, PM, and EM/PM magnetic bearings are all, in turn, a subclass of magnetic bearings, which is a subclass of the general class of bearings. Actually we could consider bearings to be a subclass of an even more general design class, such as, say, mechanical equipment, but for our purposes there is no reason to do so. In this way we have determined the root for our hierarchy. Note the general rule which is implied by our choice:

> Choose the root form to be at the highest level from which pertinent properties may be inherited,

which translates into: "be general enough, but not too general."

Now consider other possible descendents of the superclasses of our bearing. For instance, the root class of *bearing* has subclasses *ball bearing* and *roller bearing* in addition to *magnetic bearing* (as well as a plethora of others). Similarly, each of these may have subclasses. Considering the magnetic bearing subclass, there is *PM magnetic bearing* and *EM magnetic bearing* in addition to *EM/PM magnetic bearing.* With this information we can form a hierarchy.

We could, as discussed, attach our instances of magnetic bearings to the appropriate subclasses (i.e EM, PM, EM/PM). However, it's useful to subdivide the design classes first — this time by application, not functionality. That is, each type of magnetic bearing will be divided into energy storage, spindle control, and vibration isolation. To these subclasses we attach our specific bearings. (See Figure 3)

Because our example bearings are instances of a design class, they have no

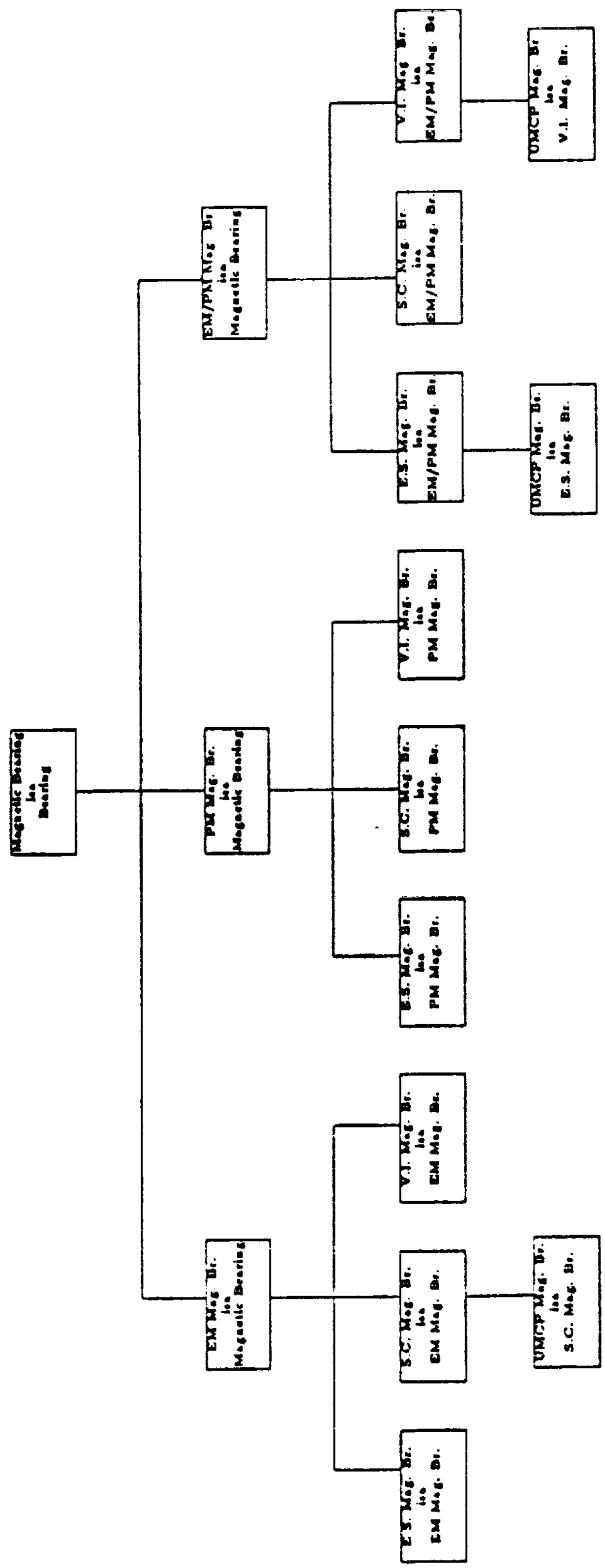

Figure 3. The Magnetic Bearing Design Hierarchy.

descendents. This leads to the question of how to represent the components of within the hierarchy. Several authors suggest an :IS-PART link analogous to the ISA link, but indicative of a component-type relationship [3, 4, 5]. This method has the unpleasant side-effect of potentially great redundancy within the DKC tree. For example, what if one-hundred different bearings all used the same control-pin design? The :IS-PART link would mean having one-hundred identical forms, representing the control-pin, spread throughout the tree: a massive waste of space. It would be better to have one control-pin form which any other form could use; this is the preferred method. This capability is implemented by creating a form representing the control-pin. Then a bearing form would represent the pin (in fact, all of its components) by a slot whose value would be a procedure which references the control-pin form. This way there is only one control-pin form; but it may be called by any number of designs. This particular mechanism highlights another very important concept:

> Forms may reference other forms through inheritance *and* through explicit procedure calls.

Now suppose we created forms for each of our components (i.e. coils, housings, plates, etc.); where should they be located within the hierarchy? Actually we do not have to insert them into the hierarchy — after all, they are not types of bearings. However, if they are not inserted, they might not be stored and recalled with the bearing hierarchy [implementation dependent], in which case we would lose them. There are several alternatives. We could create one big hierarchy with a root called something like *design* and have all our forms fit logically within this hierarchy.

This provides unlimited flexibility, but at the cost of extra effort to create. Another possibility is to make another subclass of *bearing* called *auxiliary* which

is not really a bearing subclass, but just a convenient location to store auxiliary forms for bearings.

This is very convenient, except that it becomes difficult to expand our tree beyond bearings. Also there is some inheritance confusion between *auxiliary* and *bearing*.

A third alternative is a compromise of the first two.

We could make the general *design* form to be our root. This form would have the *bearing* subclass, as well as any others we might create. Additionally, it would have the *auxiliary* subclass in which we could place our components. This strategy has several advantage:

- Auxiliary are part of the Hierarchy.
- Inheritance is no problem if *design* has no properties.
- There is one definite place to put auxiliary forms, rather than a place for each subclass.
- Only two new forms are needed (design, auxiliary), rather than the many needed to properly locate singular components.
- No effort is wasted and no extra effort is needed if a more complete hierarchy becomes necessary.

So configured, the auxiliary parts include standard items such as the bolt, nut, and epoxy. The standard nature of these components lends itself to a subclass similar to *auxiliary* that will contain standard components, as opposed to specially designed components. If we call this subclass *components*, then the complete tree for the UMCP Magnetic Bearing can be created. (See Figure 4)

The Magnetic Bearing Frames

Having created a design hierarchy for the example bearings, we have captured the knowledge implicit in the semantic relationships between design ob-

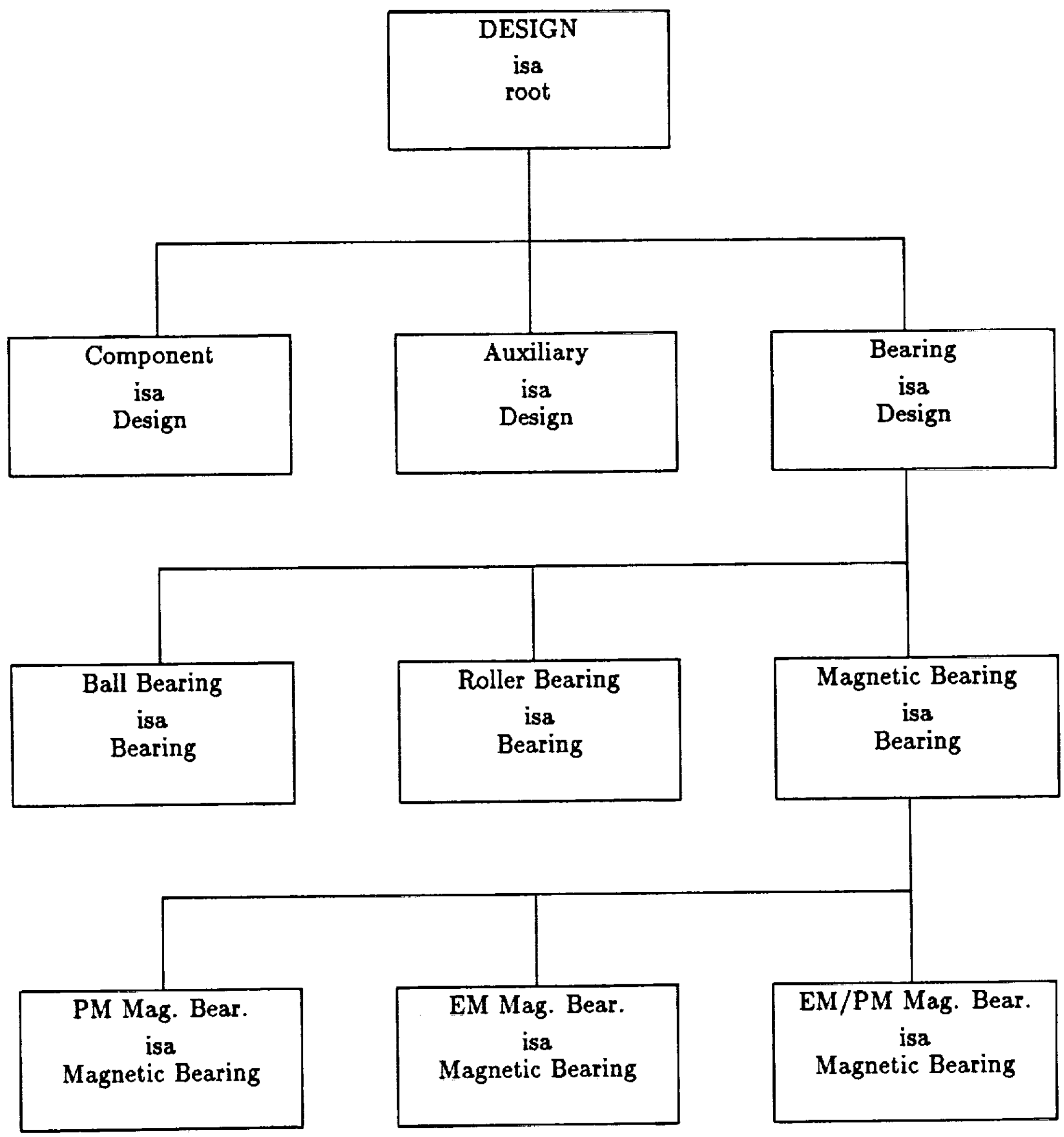

Figure 4. Complete Magnetic Bearing Hierarchy.

jects. We have not captured, however, the knowledge intrinsic to the design objects themselves. The definitive knowledge may be stored in the frames within appropriate slots: drawings, parts lists, sub-part specifications, etc. For each sample bearing there would be a *drawing* slot with an :IF-NEEDED aspect whose procedure references the assembly drawing; a set of part slots each with a :NAME aspect, a :QUANTITY aspect, an :IF-NEEDED aspect whose procedure referenced the appropriate form; and a *parts-list* slot with an :IF-NEEDED aspect whose procedure returned a list of all the parts belonging to that form. (See Figure 5)

There is some redundancy between the :NAME and :IF-NEEDED aspects for each of the part slots. At present this is necessary because inheritance requires a specific slot name, not a pattern for a slot name (i.e. partx). However, improvements to the frame system will include this capability. Note that the *drawing* and the *parts-list* slots also offer a redundancy which inheritance can simplify. Because these features are common to designs in general, we can define them within the root (*design*) frame, and let all other frames inherit the appropriate function calls. (See Figures 6a & 6b)

Frames for each of the parts of the bearing can be created similarly, but with slight differences. Consider the *control-pin* frame. The pin is an individual part: neither a design class nor an assembly. Therefore it will have unique characteristics, such as material and manufacturing specifications. Naturally the pin will have a mechanical drawing, but this is common to all designs, so the control-pin frame can inherit the appropriate procedure.

It is useful to note that the EM/PM magnetic bearing for energy storage and the UMCP pancake magnetic Bearing frames represent the class and instance categories of frames, respectively, while the Pin and UMCP pancake magnetic bearing frames represent the piece-part and assembly categories of frames, re-

UMCP Pancake Magnetic Bearing

ISA

EM/PM Mag. Bear. for Energy Storage

Drawing	:IF-NEEDED	(get-drawing)
Part1	:NAME	Magnet-Plate-Assembly
	:IF-NEEDED	(Get Magnet-Plate-Assembly)
	:QUANTITY	1
Part2	:NAME	Control-Plate
	:IF-NEEDED	(Get Control-Plate)
	:QUANTITY	2
Part3	:NAME	Control-Coil
	:IF-NEEDED	(Get Controol-Coil)
	:QUANTITY	8
Part4	:NAME	Control-Pin
	:IF-NEEDED	(Get Control-Pin)
	:QUANTITY	8
Part5	:NAME	Bolt
	:IF-NEEDED	(Get Bolt)
	:QUANTITY	1
Part6	:NAME	Nut
	:IF-NEEDED	(Get Nut)
	:QUANTITY	1
Parts-list	:IF-NEEDED	(get-parts-list)

Figure 5. Example Magnetic Bearing Frame.

DESIGN		
	ISA	
	root	
Drawing	:IF-NEEDED	(get-drawing)
Parts-list	:IF-NEEDED	(get-parts-list)

6a

UMCP Pancake Magnetic Bearing		
	ISA	
	EM/PM Mag. Bear.for Energy Storage	
Part1	:NAME	Magnet-Plate-Assembly
	:QUANTITY	1
Part2	:NAME	Control-Plate
	:QUANTITY	2
Part3	:NAME	Control-Coil
	:QUANTITY	8
Part4	:NAME	Control-Pin
	:QUANTITY	8
Part5	:NAME	Bolt
	:QUANTITY	1
Part6	:NAME	Nut
	:QUANTITY	1

6b

Figure 6. Example Design and Magnetic Bearing Frames.

spectively. Because these sets of characteristics are orthogonal, a matrix can be created to demonstrate the four possible characterizations of a given frame. (See Figure 7)

To this point we have captured design knowledge regarding the configuration of design objects (hierarchy and component specifications), and the geometric definitions of the design objects (detail and assembly drawings). However, the characteristics of the classes within the hierarchy should be considered. For example, all bearings have certain characteristics, such as load-carrying capability, frictional coefficient, etc. We need to include these slots in the *bearing* frame, and to provide appropriate default values. For the above characteristics the values depend greatly on unknown considerations (such as bearing type), so appropriate values are "wide-range." Thus any design object which inherits from *bearing* will have a default coefficient of friction of "wide-range." But any bearing, or class of bearings with a known value should specify it. A major advantage of magnetic bearings is zero friction, so the *magnetic bearing* frame will declare the friction coefficient slot to have a value of zero. The effect is that a UMCP magnetic bearing (or any other magnetic bearing) will inherit this value.

The load-carrying characteristic demonstrates a common design dilemma. For EM/PM magnetic bearings (for which the permanent magnets support the load), the load-carrying characteristics can be determined functionally by analyzing the bearing design. However, these characteristics might actually be parameters which drive the design. Therefore a knowledge capture decision must be made: is the load-carrying capability an input or an output? In this case, as in many design situations, there is a specification range (often a minimum or a maximum), any value in which is satisfactory. This lends itself to two slots: a load-carrying specification, and a load-carrying actual value. This

	Class	Instance
Assembly	EM/PM Magnetic Bearing for Energy Storage	UMCP Pancake Magnetic Bearing
Piece-part	Pin Coil	Control-Pin Control-Coil

Figure 7. Frame Classification Matrix.

way a program for calculating the actual value can be assigned to the *EM/PM Mag. Bear.* class, for all EM/PM magnetic bearings to inherit; and each specific EM/PM magnetic bearing can specify its own system requirements. Example frames containing this characteristic data are shown in Figures 8a, 8b, 9a, & 9b.

Continuing in this manner we could incorporate a wealth of knowledge about bearings, magnetic bearings, EM/PM magnetic bearings, the UMCP magnetic bearings, and any other design objects within the hierarchy. But this would be continuing to deal exclusively with the knowledge which defines and describes the design objects. Attention must be paid to the knowledge which *explains*.

Consider again the control-pin. As previously indicated, its frame would have a *material* slot; for this case the value of the slot would be "nickel iron alloy." However, at present there is no way to provide an explanation of this choice within the frame. Creating a new aspect called :DOC for the material slot solves this problem. Then by assigning this aspect a value of "to permit high flux levels on the order of 1.5 Teslas without saturation," we capture this elusive chunk of knowledge and store it systematically. (See Figure 10a)

Note that although it is cumbersome to display documentation within a graphical representation of a frame, the DKC system has no corresponding difficulty.

The :DOC aspect can be used with any slot — so every characteristic of a design object may have documentation logically associated with it. One possibility with piece-parts is to create a slot for each feature, much as assemblies have a slot for each sub-part. Not only would this allow feature inheritance, but also appropriate documentation for each feature. Such documentation might seem to do no more than verbalize information contained by the drawings. For example, a feature labelled *main-diameter* belonging to the control-pin might

Bearing

ISA

Design

Frictional Coefficient	=	wide-range
Load-Carrying Capability	=	wide-range

8a

Magnetic Bearing

ISA

Bearing

Frictional Coefficient	=	zero

8b

Figure 8. Characteristic Inheritance Frames I.

EM/PM Mag. Bear.

ISA

Magnetic Bearing

Load-Carrying Capability	:IF-NEEDED	(calc-load-cap)

9a

UMCP Pancake Mag. Bear.

ISA

EM/PM Mag. Bear. for Energy Storage

Load-Carrying Requirement	=	2g acceleration of load

9b

Figure 9. Characteristic Inheritance Frames II.

		Control-Pin
		ISA
		Auxiliary
Material	=	nickel-iron-alloy
	:DOC	to permit high flux levels on the order of 1.5 Teslas withou saturation.

10a

		Control-Pin
		ISA
		auxiliary
Material	=	nickel-iron-alloy
	:DOC	to permit high flux levels on the order of 1.5 Teslas withou saturation.
Featurel	:NAME	main-diameter
	=	$.800^{+0}_{-0.001}$ (in.)
	:DOC	to mate with the Control-Coil.

10b

Figure 10. Documentation within Frames.

have a value of 0.800 in $^{+0}_{-0.001}$, with an explanation "to mate with the control-coil." (See Figure 10b) But this does more than reiterate drawing data: it shows causality. That is, upon perusing the drawings it might be unclear whether the coil size determined the pin size or vice versa. This documentation relieves the ambiguity, and redirects attention to the appropriate form.

The part slots within an assembly form may use the :DOC aspect in an analogous fashion to feature slots of piece-parts. Considering the pancake bearing, and specifically the part4 slot (control-pin), it's clear that the documentation for any slot should do two things:

- explain the need/use of the part.
- explain any additional information.

For part4 this means:

- explain the need/use of the control-pin.
- explain why there are eight (8).

Similar documentation would be appropriate for other slots. Additionally, a documentation slot could be created to contain general information about the entire object. Figure 11 shows the example frame with these modifications. Figures 12 and 13 show, respectively, the spindle control and vibration isolation example bearing frames.

The Magnetic Bearing Knowledge Base

Having developed an understanding of magnetic bearings, the frames which represent them, and the hierarchy in which they fit, we can populate the knowledge base. For purpose of example, a few parts from each of the UMCP magnetic bearings were considered and implemented. In certain cases there was similarity between parts of different bearings, and when appropriate, DKC mechanisms were used to take advantage of it.

UMCP Pancake Magnetic Bearing

ISA

EM/PM Mag. Bear. for Energy Storage

Documentation	:GOAL	support an energy storage flywheel
Part1	:NAME	Magnet-Plate-Assembly
	:QUANTITY	1
	:DOC	the permanent magnet sub-assembly
Part2	:NAME	Control-Plate
	:QUANTITY	2
	:DOC	top and bottom plates (contain the electro-magnets)
Part3	:NAME	Control-Coil
	:QUANTITY	8
	:DOC	to generate controlling magnetic fields
Part4	:NAME	Control-Pin
	:QUANTITY	8
	:DOC	conductive center structure for control-coils
Part5	:NAME	Bolt
	:QUANTITY	1
	:DOC	stack fastener
Part6	:NAME	Nut
	:QUANTITY	1
	:DOC	stack fastener

Figure 11. UMCP Energy Storage Magnetic Bearing Frame.

UMCP Spindle Control Magnetic Bearing

ISA

EM Spindle Control Magnetic Bearing

Documentation	:GOAL	Control of a High-Accuracy Machining Spindle
Part1	:NAME	Spindle
	:QUANTITY	1
Part2	:NAME	Thrust Bearing Upper Plate
	:QUANTITY	1
Part3	:NAME	Thrust Bearing Lower Plate
	:QUANTITY	1
Part4	:NAME	Thrust Bearing Coil
	:QUANTITY	2
Part5	:NAME	Radial Sensor Ring
	:QUANTITY	2
Part6	:NAME	Axial Sensor Ring
	:QUANTITY	1
Part7	:NAME	Radial Bearing Top Assembly
	:QUANTITY	1
Part8	:NAME	Radial Bearing Lower Assembly
	:QUANTITY	1
Part9	:NAME	Spindle Housing
	:QUANTITY	1

Figure 12. UMCP Spindle Control Magnetic Bearing Frame

UMCP Vibration Isolation Magnetic Bearing

ISA

EM/PM Vibration Isolation Magnetic Bearing

Documentation	:GOAL	isolate vibrations of a rotating load
Part1	:NAME	Central Ring
	:QUANTITY	1
Part2	:NAME	Flux Ring
	:QUANTITY	2
Part3	:NAME	Pole Piece
	:QUANTITY	8
Part4	:NAME	Aluminum Housing
	:QUANTITY	2
Part5	:NAME	Draw Rod
	:QUANTITY	8
Part6	:NAME	Electromagnet Coil
	:QUANTITY	8
Part7	:NAME	Socket Head Cap Screw
	:QUANTITY	8
Part8	:NAME	Wave Washer
	:QUANTITY	8
Part9	:NAME	Touchdown Ball Bearing
	:QUANTITY	2
Part10	:NAME	Position Transducer Sensor
	:QUANTITY	2
Part11	:NAME	RECO Permanent Magnet
	:QUANTITY	16
Part12	:NAME	Rotor Spindle Sleeve
	:QUANTITY	1

Figure 13. UMCP Vibration Isolation Magnetic Bearing Frame.

The magnet plate is the first part of the pancake bearing to be designed. The principal parameters are diameter, thickness, pole face angle, pole face thickness, and material saturation level. These five parameters are independent, and different combinations will yield different bearing characteristics. The selection of these values is based upon experience, intuition, and iterative testing. However, certain heuristic knowledge exists:

- pole face thickness $\leq 1/16\times$ diameter
- plate thickness $\geq 1.75\times$ pole face thickness This knowledge is incorporated as a recommended range which a designer may accept or override. But he either case, he has referenced the information.

The electromagnetic coils of the pancake bearing have much less independence than the magnet plates. The fundamental parameters are diameter, wire diameter, and number of turns. The diameter is determined uniquely by the control-pin diameter. Therefore the coil frame has a slot labelled "diameter" with an :IF-NEEDED aspect that fetches the pin diameter and processes it appropriately (determined by type of fit). The wire diameter is constrained by several other parameters, so that slot has a procedure to calculate the resultant constraint. The number of turns is constrained by flux requirements and space limitations, but is not determined uniquely. Therefore, when a value is specified an :IF-ADDED procedure checks for consistency and returns appropriate information. The coil, thus, has demonstrated a significant difference regarding design constraints. If the constraints uniquely determine the value, then an :IF-NEEDED function can be attached for this purpose. But if the constraints only restrict the value, then an :IF-ADDED may be implemented to assure this.

The riser block of the UMCP spindle control magnetic bearing provides a mechanical interface between the spindle assembly and the machine body.

The most obvious features, the holes, are determined by the mounting holes on the mating surfaces. Also, the block thickness is determined by spindle position requirements. As before, these values are implemented via :IF-NEEDED aspects. The remaining riser block parameters are less clear-cut. The material, aluminum, is based upon weight minimization given strength and stiffness requirements. In reality, aluminum was chosen because the designer knew it was appropriate. In theory, the strength and stiffness requirements would be specified and an :IF-NEEDED procedure would select the lightest available material (from a data base) which satisfied these conditions.

The complex face geometries correspond to the most interesting design knowledge of the block. As with material, the driving influence was weight minimization given the strength and stiffness requirements. As there are innumerable configurations, the design must be based upon experience, and, probably, some limit case analyses. This demonstrates the difficulty of applying DKC to the synthesis phase of design.

The UMCP vibration isolation magnetic bearing, like most magnetic bearings, can maintain suspension as long as displacements are small (due to nonlinearities). Therefore ball-bearings are incorporated into the design to act as a backup system. Before the rotor can displace too far, it will engage the backup bearings and allow the magnetic circuitry to re-effect suspension. The design of the backup bearings is a two part job. First is to determine the radius; second is the actual bearing design, which is associated with the ball-bearing sub-class of the general bearing hierarchy. Determining the radius requires calculating the range of static controllability, which in turn requires knowing the maximum bearing force and the static stiffness. Then, as a rule-of-thumb, the backup bearing is given a radius 90% of the range of static controllability. Because

this method determines exactly the backup bearing radius, it is implemented with an :IF-NEEDED. However, the procedure assumes it will be able to find (or compute) the force and stiffness. If this data had not been established previously, the :IF-NEEDED would not have succeeded. Additionally, once the radius is known, the actual ball bearing design is implemented with an :IF-NEEDED; but because the ball-bearing hierarchy is empty, this procedure is inoperative.

The design methodology for the electromagnet coils is similar to that for the coils of the pancake bearing. So rather than duplicating that information, one coil frame describes the general methodology, and each bearing accesses that frame. Moreover, because the methodology is (usually) appropriate for any EM/PM magnetic bearing, we can place the link to the coil frame within the EM/PM magnetic bearing subclass frame, and let all our instances inherit from it.

In many case we may have defined already a design object in several locations. This actually occurred with the coil of the preceding section. In these situations it is appropriate to locate every such occurrence and replace them with pointers to a single frame. Fortunately the DKC search functions and frame manipulation functions simplify this process into a few basic commands. Indeed, a macro could (and should) be written to do all this in one step.

Recommendations and Conclusions

The future of Design Knowledge Capture depends upon its development now. This thesis has presented many critical aspects of DKC, but a lot of additional work will be needed before an initial attempt at a complete system can be implemented. This work can be divided into three main categories:

- System Definition and Coding
- Computer Science Development

- Prototyping

The initial DKC system presented here provides a template for increasingly sophisticated system definition; many of these definitions will be motivated by advances in the field of knowledge engineering. Therefore it is immensely important to monitor the state-of-the-art of knowledge engineering, expert systems, and related areas of AI. As we have discovered, AI techniques are the only tools available for generating this type of system, and AI is a fast-paced and ever-changing field.

Many other improvements of the DKC definition will come from the experience of developing code to satisfy existing definitions. Frequently the development of computer code produces a heightened awareness of a more general problem. This translates into superior system definition, and the cycle continues. Therefore, there must be a continued, dedicated effort to develop code implementing the current definition even though it may cause its own obsolescence: that is precisely the point. However, when developing code, it would be worthwhile to follow the maxim:

write tools, not programs.

This means that programs should not be "hacked" together just to get something working, but developed systematically to assure future compatibility and expandability. Some areas where the system definition might be enhanced are:

- Additional frames commands.
- Additional slot aspects (e.g. :DOC, :IS-PART).
- Multiple parents ($\Rightarrow$ resolution of inheritance ambiguities).
- Procedural calls to other environments (e.g. call a DOS-based design program).

This research has made the following specific contributions:

- Determination that frame-based systems provide a useful methodology for management and application of design knowledge.
- Definition of specific user interface requirements; this consists of a window-based browser.
- Specification of syntax for DKC commands.
- Demonstration of the feasibility of DKC by application to existing designs.

Future considerations for the advancement of DKC include creating the graphic interface, prototyping many different systems, monitoring the state-of-the-art in related areas, and increasing the involvement of computer science personnel.

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